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Abstract

As one of the most energy-intensive and polluting industries, ammonia production is responsible for significant carbon dioxide (CO_2) and air-pollutant emissions. Although many energy-efficiency measures have been proposed by the Chinese government to mitigate greenhouse gas emissions and improve air quality, lack of understanding of the cost-effectiveness of such improvements has been a barrier to implementing these measures. Assessing the costs, benefits, and cost-effectiveness of different energy-efficiency measures is essential to advancing this understanding. In this study, a bottom-up energy conservation supply curve model is developed to estimate the potential for energy savings and emissions reductions from 26 energy-efficiency measures that could be applied in China's ammonia industry. Cost-effective implementation of these measures saves a potential 271.5 petajoules/year for fuel and 5,443 gigawatt-hours/year for electricity, equal to 14% of fuel and 14% of electricity consumed in China's ammonia industry in 2012. These reductions could mitigate 26.7 million tonnes of CO_2 emissions. This study also quantifies the co-benefits of reducing air-pollutant emissions and water use that would result from saving energy in China's ammonia industry. This quantitative analysis advances our understanding of the cost-effectiveness of energy-efficiency measures and can be used to augment efforts to reduce energy use and environmental impacts.

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Acronyms

BAT	best available technology
CASS	Chinese Academy of Social Science
$CCE_{electricity}$	cost of conserved electricity
CCE_{fuel}	cost of conserved electricity
CFETS	China Foreign Exchange Trading System
CNFA	China Nitrogen Fertilizer Industry Association
CO	carbon monoxide
CO_2	carbon dioxide
CPCY	China Petrochemical Corporation Yearbook
CSC	conservation supply curve
ECSC	electrical conservation supply curve
FCSC	fuel conservation supply curve
FYP	five-year plan
GHG	greenhouse gas
GJ	gigajoule
GWh	gigawatt-hours
IEA	International Energy Agency
IETD	Industrial Efficiency Technology Database
IFA	International Fertilizer Industry Association
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kgce	kilograms coal equivalent
Kt	kiloton
KWh	kilowatt-hour
MDEA	N-methyldiethanolamine
MIIT	Ministry of Industry and Information Technology
Mt	million tonnes
Mtce	million tonnes of standard coal equivalent
MWh	megawatt-hour
NBS	National Bureau of Statistics
NDRC	National Development and Reform Commission
NOx	nitrogen oxides
O&M	operations and maintenance

PJ	petajoule
PM_{10}	10-micron particulate matter
RMB	renminbi
SEC	specific Energy consumption (denotes energy used for per unit production)
SO_2	sulfur dioxide
TJ	terajoule

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1. Introduction

According to the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), industry-related emissions of greenhouse gases (GHGs) have continued to increase and are higher than emissions from other end-use sectors. Industrial GHG emissions represented a little more than 30% of global GHG emissions in 2010 (IPCC 2014). One of the most energy-intensive industrial processes is the production of chemical materials and products.

In China's chemical industry, ammonia production consumes the most energy and emits the most carbon dioxide (CO_2) (CNFIA 2012). The world's ammonia production has increased rapidly since 2002, and China is the largest producer, with total annual ammonia production of 54.6 million tonnes (Mt) in 2012. This represents approximately one-third of the world's total ammonia production (IFA 2014). Figure 1 shows the production of ammonia in different regions of the world. China produces large amounts of ammonia for use in manufacturing synthetic fertilizer, which is used to meet the growing food demand (Wang 2013).

At the same time, climate change, air pollution, and water scarcity are three main challenges in China. These problems are closely related to the production and consumption of energy, including mining and extraction of raw coal and crude oil as well as generation of heat and electricity (Li et al. 2012). The Chinese ammonia industry consumes significant amount of energy and emits substantial amounts of CO_2 and other air pollutants, including sulfur dioxide (SO_2), nitrogen oxides (NOx), and 10-micron particulate matter (PM_{10}). These pollutants contribute to significant regional and global environmental problems. In addition, the ammonia industry is a major water user. Its water withdrawal[1] and consumption is much higher than those of many other chemical subsectors, as shown in Figure 2 (MIIT 2012a).

[1] The United States Geological Survey defines "water withdrawal" as the amount of water removed from the ground or diverted from a water source for use. "Water consumption" refers to the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment (USGS 2010).

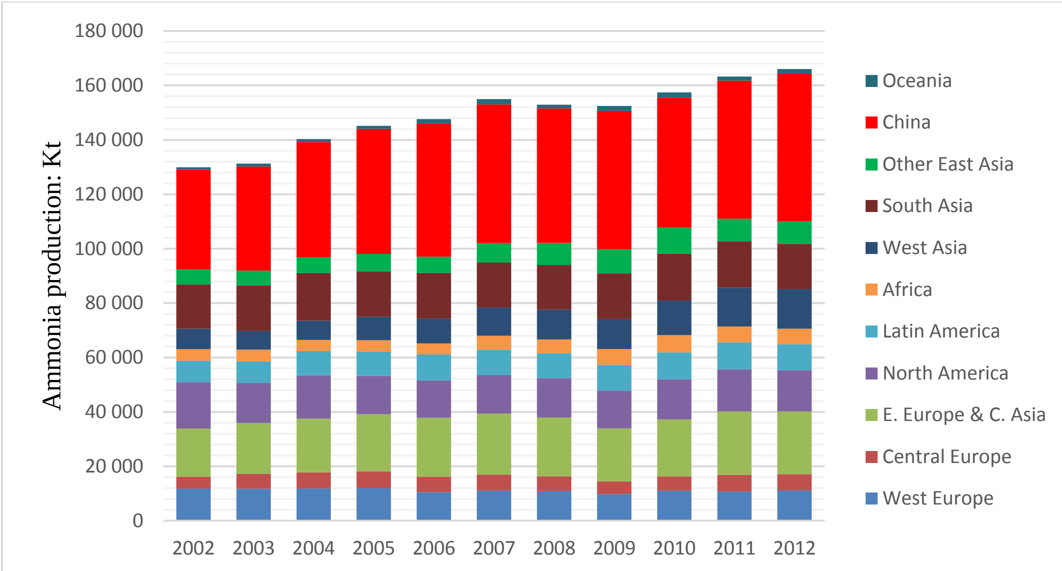

Figure 1. World ammonia production by region, 2002-2012 （IFA 2014）

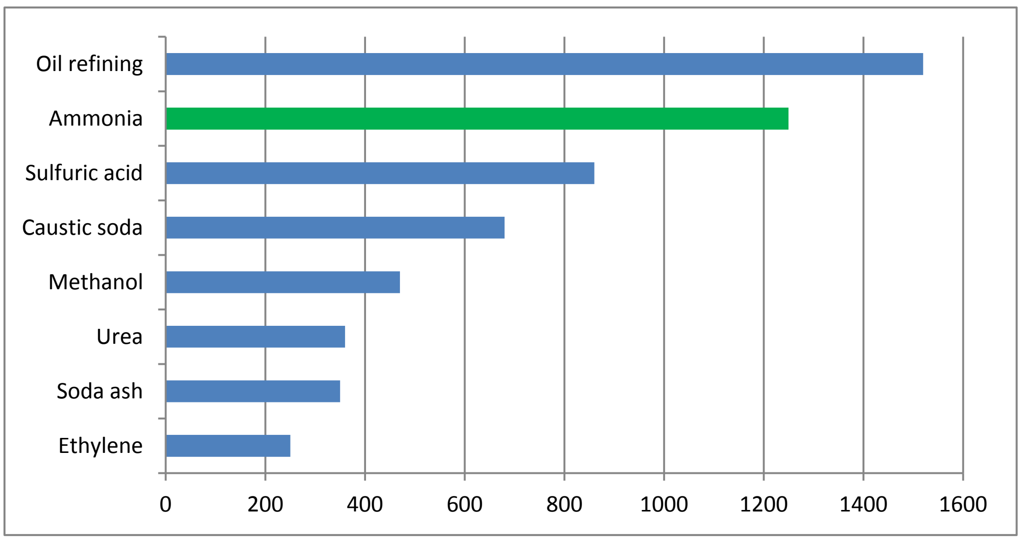

Figure 2. Water withdrawal in different chemical industry subsectors and oil refining in 2010 (in million cubic meters) (MIIT 2012a)

Energy conservation is very important for the mitigation of climate change and the improvement of air quality. Given its high energy consumption and high emissions, China's ammonia industry must play a vital role in national energy-saving and emissions-reduction programs. To improve the energy efficiency and reduce air emissions, Chinese government has implemented many measures. During 2008-2013, the National Development and Reform Commission (NDRC) released series of *National Extension Directory of Important Energy Conservation Technologies* (NDRC 2008, 2009, 2011a&b, 2012, 2013); the Ministry of Industry and Information Technology (MIIT) also established the Energy Conservation and Emission Reduction Information Platform and released *The Advanced Technology Catalog of Energy Conservation* *and Emissions Reduction in Petrochemical Industry* in 2012 (MIIT 2012b). All of these government agencies have proposed series of energy-efficiency measures for the ammonia industry, which raises the question of how to quantitatively evaluate and select the most suitable and cost-effective measures.

In addition to reducing greenhouse gas (GHG) and air-pollutant emissions, energy-efficiency policies and programs also help reduce water use. However, assessment and evaluation of energy-efficiency measures often take into account only energy savings, CO_2 emissions reductions, and associated costs; air-pollution and water use co-benefits of energy-efficiency policies and programs are typically not included in an impact analysis. Awareness of these additional benefits is important for policy makers to understand the overall benefits of energy-efficient technologies.

In the remainder of this report, we give a brief overview of China's ammonia industry and then describe the methodology used in this study, including data collection, basic assumptions, development of the energy conservation supply curve (CSC), and quantification of co-benefits. Next, we estimate the potential reduction in air-pollutant (SO_2, NOx, and PM_{10}) emissions and water consumption that would result from adopting energy-efficiency measures. We conclude with a discussion of our results—including the energy-saving potential and associated costs of the efficiency technologies, the energy CSC, and our co-benefits and sensitivity analyses—and, finally, our recommendations.

2. Overview of the China's ammonia industry

2.1 Ammonia production and consumption

Ammonia products can be divided into two main categories: agricultural and industrial. Agricultural ammonia was mainly used to produce other chemicals such as urea, ammonium nitrate, ammonium bicarbonate, ammonium sulfate, and ammonium chloride, which are primarily used in fertilizers. Industrial ammonia is mainly used for producing nitrate, soda ash, and acrylonitrile, which are used for other chemical products (Wen 2012). In 2010, agricultural ammonia was mainly used to produce urea and ammonium bicarbonate, which accounted for approximately 75% of the total in China. The remainder was split with ammonia nitrate and ammonium chloride, which accounted for approximately 15% of the total. Industrial ammonia accounted for about 10% in the same year (Han 2010). From 2000 to 2012, China's production of nitrogen fertilizer increased approximately 5% per year, from 24.0 to 43.1 Mt. During the same period, the total production of ammonia in China grew at 4% per year, increasing from 33.6 Mt to 54.6 Mt (CNFA 2013). Table 1 shows the changes in Chinese ammonia production and consumption from 2006 to 2012 (Wen 2012, CPCY 2013, Wang 2013).

Table 1. Chinese production and consumption of ammonia, 2006-2012

Year	Production	Import	Export	Apparent consumption	Self-sufficiency rate[2]
	Mt	Mt	Mt	Mt	%
2006	49.38	0.19	0	49.57	99.6
2007	51.59	0.23	0	51.82	99.6
2008	49.95	0.24	0	50.19	99.5
2009	51.36	0.28	0	51.64	99.5
2010	49.63	0.29	0	49.92	99.4
2011	50.69	0.29	0	50.98	99.4
2012	54.59	0.34	0	54.92	99.4

In 2010, there were 496 Chinese ammonia enterprises, of which 74 were large scale (production capacity greater than 0.3 Mt/year [yr]) and were responsible for 49% of the total production capacity in that year. Medium-scale ammonia enterprises (production capacity between 0.08 Mt/yr and 0.3 Mt/yr) numbered 149 and accounted for 33% of the total capacity. The remaining 273 small-scale ammonia enterprises (production capacity less than 0.08 Mt/yr) represented 18% of the total capacity (ERI 2013a).

In China, natural gas is mainly located in the central and western regions, but the primary demand is located in the east. Sichuan province (in the west) has a lot of natural gas reserves, and so ammonia production in this area relies heavily on natural gas, with additional natural-gas-based production in Xinjiang, Neimenggu, and Hainan provinces. The areas that rely mainly on coal to produce ammonia are Shandong, Henan, Shanxi, Hubei, Sichuan, Hebei, Jiangsu, and An'hui provinces (Wang 2013). Table 2 shows the capacity and production of ammonia at the province level in China in 2010 (Coal-chemical Industry 2011).

Table 2. Capacity and production of ammonia at the province level in China, 2010

Region	Capacity	Production	Region	Capacity	Production
	Mt/yr	Mt		Mt/yr	Mt
Henan	5.2	4.28	Guangxi	1.2	0.90
Shandong	8.0	6.63	Shanxi	1.5	1.22
Hebei	3.6	2.96	Sichuan	4.8	4.03
Shanxi	5.0	4.19	Guizhou	2.2	1.75
Anhui	3.5	2.66	Yunnan	2.4	2.20
Hubei	4.8	3.92	Xinjiang	1.8	1.48
Hunan	2.0	1.64	Dongbei	2.8	2.14
Jiangsu	4.0	3.16	Zhejiang	0.8	0.50
Fujian	1.2	1.02	Other regions	3.2	5.14
Total	58.0	49.63			

[2] The self-sufficiency rate is the ratio between national ammonia production and ammonia consumption.

2.2 Ammonia feedstock

Ammonia is produced by the reaction of hydrogen and nitrogen, known as the “Haber-Bosch process.” Depending on the feedstock used, the two main hydrogen production processes used in ammonia production are:

（1）Steam/air re-forming process. Feedstocks include natural gas or other light-carbon fuels such as natural gas liquids, liquefied petroleum gas, and naphtha.

（2）Partial oxidation process. Feedstocks include heavy oils and coal (IETD 2014).

Figure 3 shows ammonia production processes using different feedstocks.

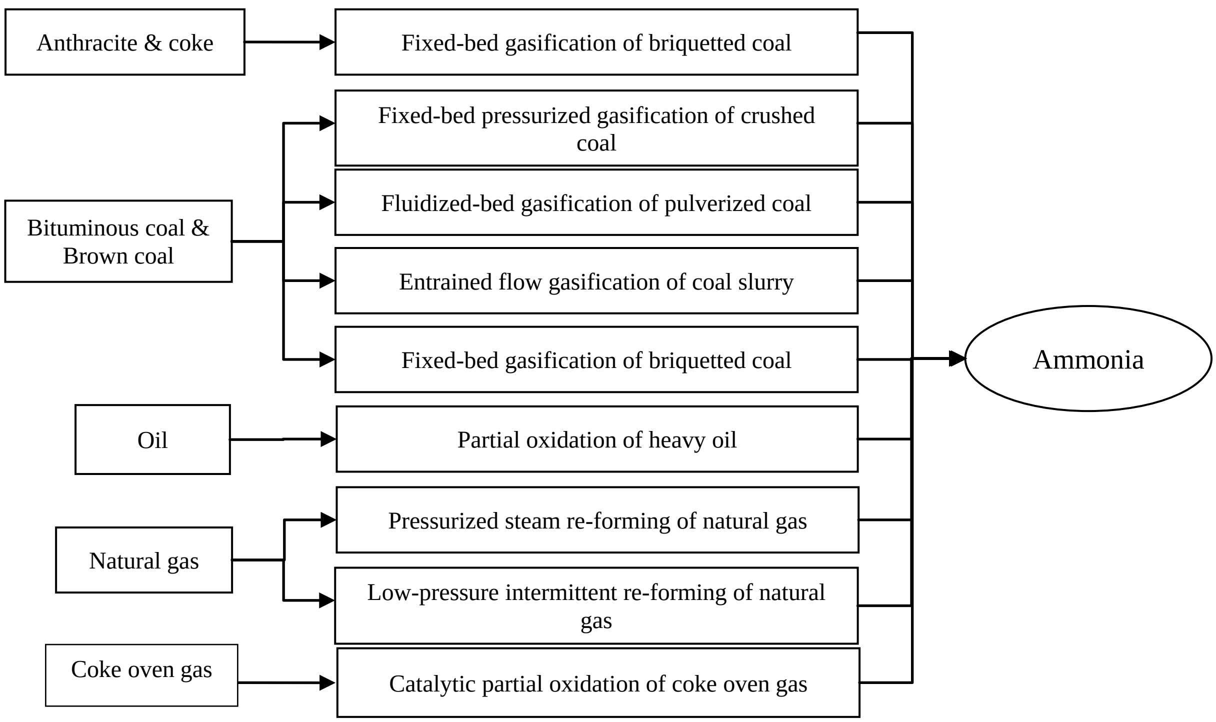

Figure 3. The ammonia industry’s main production processes (Zhang et al. 2012)

Globally, about 72% of ammonia is produced using natural gas and the steam re-forming process. Coal is the primary feedstock for hydrogen production in ammonia plants in China. The type of feedstock plays a significant role in the amount of energy used and CO_2 produced. Natural-gas-fueled production is the least energy intensive. Coal-based production generally has the highest energy consumption and CO_2 emissions (IETD 2014).

In China, coal gasification is the most widely used feedstock because of China’s abundant coal resources compared to relatively scarce natural-gas reserves. In contrast, in Europe and North America, natural gas is the dominant ammonia production feedstock (Zhou et al. 2010). In 2011, the shares of coal-based, natural-gas-based, and other-fuel-based ammonia production in China were 76% , 21%, and 3%, respectively (Han 2012).

3. An overview of energy consumption in China's chemical and ammonia industries

3.1 Energy consumption in China's chemical industry

Closely following the ferrous metals industry, the chemical industry is the second largest energy consumer in China (see Figure 4). During 2007-2012, the final energy consumption in the chemical industry increased from 404.0 to 501.0 Mt of standard coal equivalent (Mtce) (NBS 2013). Out of this 500 Mtce, the energy consumed in 2012, for petroleum processing, coking, and nuclear-fuel processing subsector was approximately 137.2 Mtce whereas the energy consumed for manufacturing raw chemical materials and chemical products subsector was significantly more, approximately 363.8 Mtce (NBS 2013).

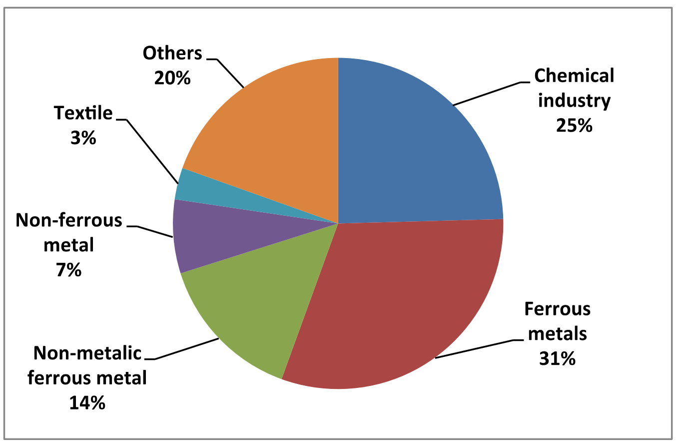

Figure 4. Share of final energy consumption of different manufacturing subsectors in China in 2012 (NBS 2013)

Within the chemical industry, ammonia production consumes the most energy. Figure 5 shows the final energy consumption of different chemical industry subsectors in China (CASS 2011).

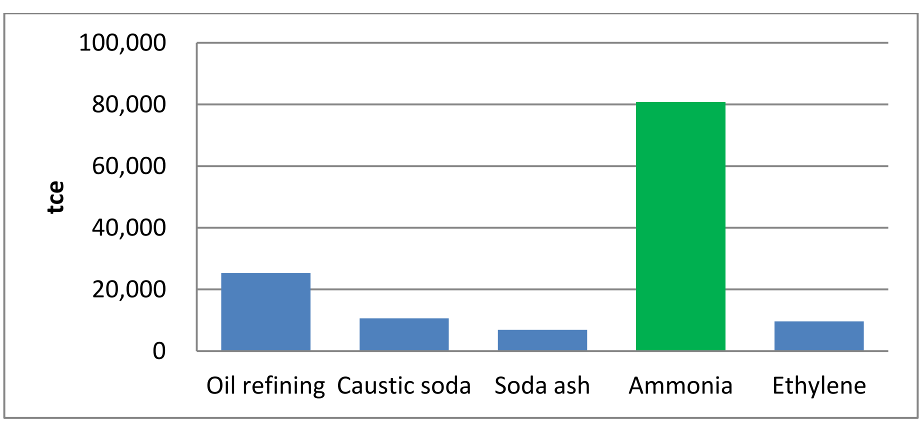

Figure 5. Energy consumption of the main chemical industry subsectors in China in 2008 (CASS 2011)

3.2 Energy consumption in China's ammonia industry

If compared with other countries or regions, the energy intensity for China's ammonia production is the highest. Within the ammonia production process, gas generation uses the most energy – 60-70% of the total energy consumption at global level. Nevertheless, the energy intensity of China's ammonia industry, which is mostly coal-based, is higher that than many other countries or regions where natural-gas-based ammonia production is dominant.

Energy consumption per tonne of ammonia produced in China has dropped during recent decades, but there is still room for improvement (ERI 2013a). Table 3 shows the energy intensity of three typical ammonia plants in China using different feedstocks. The natural-gas-based ammonia plant consumes the least energy per unit production and can produce extra electricity and steam through heat recovery. The data in Table 3 also show that fuel consumption is the largest contributor to total energy consumption (Zhou et al. 2010).

Table 3. Energy consumption of typical Chinese ammonia plants with different feedstocks (Zhou et al., 2010)

Plant	Weihe	Ningxia	Zhongyuan
Feedstock	Coal	Oil	Natural gas
Fuel intensity	1.38 tonnes coal /tonne	0.73 tonne oil/tonne	893 cubic meters /tonne
Electricity intensity (Kilowatt-hour/tonne)	139.3	75.0	-51.8
Steam use (ton steam/tonne)	2.0	1.4	-1.9

During the past decade, China's ammonia industry has made significant efforts to phase out outdated, inefficient, small production facilities and adjust the feedstock structure to improve energy efficiency and decrease pollution. In 2013, MIIT released minimum energy performance standards for the ammonia industry based on feedstock, as shown in Table 4 (MIIT 2013c).

Table 4. Minimum energy performance standards for existing and new ammonia production facilities (MIIT 2013c)

Feedstock	Energy intensity (gigajoule/ton)	
	Existing	New
High-quality anthracite	≤55.7	≤43.9
Ordinary anthracite, Coke, Briquette	≤64.4	≤52.7

Natural gas, Coke oven gas	≤48.3	≤33.7

4. Methodology

In order to quantify the energy-saving and emission reduction potentials and to characterize the associated costs and co-benefits, we used the compiled data and information and applied the energy CSC for this research. This chapter describes the data collection, basic assumptions, and the analysis approach.

4.1 Data collection

Many energy-efficiency technologies promoted by NDRC and MIIT are used in this analysis because other studies do not provide consistent and comprehensive data on energy savings, costs, and lifetimes of various technologies (NDRC 2008, 2009, 2011a&b, 2012, 2013; MIIT 2012b). For some technologies, information was obtained from other sources (Zhang et al. 2012, ERI 2013a&b, IETD 2014).

We used 2012 as the base year because that is the latest year for which energy and environmental data have been published by China's National Bureau of Statistics (NBS 2013). Data on the ammonia production were obtained from National Bureau Statistics (NBS 2013) and the academic literature (Wen 2012, Zhang et al. 2012, ERI 2013a&b, Wang 2013). To estimate the penetration rates of different energy-efficiency measures in 2012, we developed a questionnaire and sent it to experts[3] in the Chinese ammonia industry. Additionally, we obtained data from two recent reports: *Key industrial energy-efficient and emission reduction technologies and measures* (MIIT 2011) and *Roadmap study on achieving technical energy conservation potential in Chin*a's *industrial sector by 2020* (ERI 2013a).

4.2 Basic assumptions

To calculate comparable energy use values, we have to convert into energy values the physical quantities of fuel consumed to produce ammonia. Conversion factors must also be used to calculate electricity use (Hasanbeigi et al. 2014).

We used a conversion factor of 2.9 KWh/kgce to convert electricity from final energy to primary energy. This factor was derived by combining China's 2012 national average net heat rate for fossil-fuel-fired power generation, 0.33 kilograms of coal equivalent (kgce) per kilowatt-hour (KWh), and national average transmission and distribution losses of approximately 6.74% (China Power Yearbook 2013). We used the lower heating value of fuel for our analysis. To convert costs reported in renminbi (RMB) to U.S. dollars (US$), we used an average exchange rate of 6.31 RMB/US$ (CFETS 2013).

[3] We sent the questionnaire to five experts in China and received responses from three: Su Jianying (CNFIA), Tongqing (Tsinghua University), and Guo Shiyi (MIIT).

To calculate CO_2 emissions from energy consumption, we used carbon conversion factors for fuels from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2007). The emissions factor for grid electricity in 2012 was assumed to be 0.773 kilograms (kg) CO_2/KWh (NBS 2013). Nearly 90% of the fossil fuel used in China's ammonia industry is coal. Therefore, we used the weighted average CO_2 emission factor for raw coal, cleaned coal, and other washed coal consumed in the chemical industry in 2012 and the weighted value of approximately 83.8 kg CO_2/gigajoule (GJ) as the CO_2 emission factor for fuel (NBS 2013; IPCC 2007).

The average unit price of electricity was assumed to be 760 RMB/megawatt-hour (MWh) (China Electricity Council 2013). For the fuel price, we used the average 2012 unit price of thermal coal for industrial use, which was approximately 700RMB/tonne (CCTD 2013).

Additionally, we assumed that the energy efficiency measures are mutually exclusive and there is no interaction between them (Hasanbeigi, 2013). For this reason and to avoid overestimation of total cumulative energy saving potential, we have assumed a lower end of energy saving range that was available for each energy efficiency measure.

4.3 Energy conservation supply curve

We used the concept of a CSC to construct a bottom-up model for estimating the cost-effective and technical potential for energy-efficiency improvements in China's ammonia industry. The CSC is an analytical tool that captures both the engineering and the economic perspectives of energy conservation. The CSC shows energy conservation potential as a function of the marginal cost of conserved energy (CCE) and has been used to assess energy-efficiency potential in different industries. Examples are the energy CSC developed by Lawrence Berkeley National Laboratory for the iron and steel, cement, and pulp and paper industries in China, Thailand, and the U.S. (Laitner et al. 2001, Worrell et al. 2003, Hasanbeigi et al. 2010, Hasanbeigi et al. 2012a&b, Kong et al. 2013). McKinsey has used this concept to develop GHG abatement cost curves for different countries (McKinsey 2007).

An energy CSC can be developed for a plant, a group of plants, an industry, or an entire economic sector.

The CCE required for constructing the energy CSC was calculated using Eq. (1):

$$CCE = \frac{Annualized\ Captial\ Cost + Annual\ Change\ in\ O\ \&\ M\ Costs}{Annual\ Energy\ Savings} \tag{1}$$

where *CCE* denotes the cost of conserved energy for an energy-efficiency measure and *O&M Costs* denotes the cost of operations and maintenance.

The annual fuel savings and electricity savings were calculated as follows:

$$SF = P \times RF \times Potential\ Adoption\ Rate \tag{2}$$

$$SE = P \times RE \times Potential\ adoption\ rate \tag{3}$$

where

SF = fuel savings (GJ);

SE = electricity savings (KWh);

P = ammonia production (Mt);

RF = fuel savings per ammonia production (GJ/Mt);

RE = electricity savings per ammonia production (KWh/Mt).

We obtained the penetration rate of each measure in 2012 by consulting with experts and reviewing the literature that shows the adoption rate of each measure in the base year. For most of the measures, the full potential adoption rate cannot be fully implemented for technical and plant-specific reasons. Thus, we calculated the "potential adoption rate" for our analysis using Eq. (4).

$$Potential\ Adoption\ Rate = (100\% - Penetration\ Rate) \times \frac{Technical\ Applicability}{100\%} \qquad (4)$$

where the *Penetration Adoption Rate* is the current adoption rate of the technology, and the *Technical Applicability* is the extent to which the remaining penetration potential of the technology can be feasibly realized in the Chinese ammonia industry. Both of these rates were obtained based on consultation with experts in the Chinese ammonia industry.

Take energy-efficiency measure #1 as an example. The penetration rate of this measure in the Chinese ammonia industry was 20% in 2012, which means that, if this measure could feasibly be adopted in every Chinese ammonia mill, its remaining or potential adoption rate would be 80%. However, in reality, technical and plant-specific conditions prevent this efficiency measure from being applied in some plants. If we assume that the actual adoption rate for this measure is 50%, the potential adoption rate is equal to 40% [(100%-20%)*(50%/100%)].

The annualized capital cost can be calculated from Eq. (5):

$$Annualized\ capital\ \cos t = Capital\ \cos t \times d\ /\ (1-(1+d)^{-n}) \qquad (5)$$

where d is the discount rate, and n is the lifetime of the energy-efficiency measures (in years).

A real discount rate of 30% was used for the base-case analysis to reflect the barriers to energy-efficient investment in China's ammonia industry. These barriers include perceived risk, lack of information, management concerns about production and other issues, capital constraints, opportunity costs, and the preference for short payback periods and high internal rates of return (Hasanbeigi et al. 2012a,b).

After separately calculating the CCE for each energy-efficiency measure, we constructed the energy CSCs for fuel- and electricity-saving measures by ranking all of those measures in ascending order according to their CCEs. For each CSC, we determined an energy price line: the weighted average fuel price CSC (FSCS) and the average electricity price CSC (ECSC) for the ammonia industry. All measures that fell below the energy price line were considered cost-effective. Furthermore, the CSCs show the total technical potential for electricity or fuel savings accumulated from all the applicable measures on each curve. On the curve, the width of each measure (plotted on the x-axis) represents the energy-saving potential of that measure in the base year. The height (plotted on the y-axis) shows the measure's CCE, calculated as explained above.

To construct the energy CSCs, we took the following steps:

1. We established 2012 as the base year for energy, materials use, and production in the ammonia industry in China.
2. We developed a list of commercially available energy-efficiency measures for the ammonia industry to include in the construction of the CSCs. A total of 26 energy-efficiency measures are included in this study based on their applicability to China's ammonia industry as well as availability of data about them.[4]
3. We determined the potential adoption rate of these energy-efficiency measures in the base year, using information collected from China's ammonia companies, expert judgment, and a literature review, using the method explained above.

We constructed the FCSC or ECSC separately, to capture the accumulated cost-effectiveness and total technical potential for electricity- and fuel-efficiency improvements. For this purpose, we calculated the CCE for each technology. After calculating the CCE_{fuel} or $CCE_{electricity}$ for all measures, we ranked the measures by ascending CCE_{fuel} or $CCE_{electricity}$ to construct the FCSC or ECSC, respectively. The reason to construct two separate supply curves for electricity and fuel is that the cost-effectiveness of energy-efficiency measures depends strongly on energy prices. Because average electricity and fuel prices differed in the ammonia industry in 2012, and because many technologies save only electricity or only fuel, we separated the electricity- and fuel-saving measures. Thus, the FCSC with average unit price of electricity plots technologies that primarily save electrical energy, and the ECSC with average unit price of fuel plots technologies that primarily save fuel. Some measures save both electricity and fuel, and some increase electricity consumption as a result of saving fuel. When a technology's fuel savings accounted for the larger portion of total primary energy savings than electricity savings, we included this technology only in the FCSC but not the ECSC.

Although the CSC method we developed is a good screening tool for evaluating potential energy-efficiency improvements, the actual cost and energy-savings potential of each energy-efficiency measure can vary depending on several factors, such as raw material quality, technology provider, production capacity, byproducts, and the time period of the analysis. Moreover, some energy-efficiency measures provide additional productivity and environmental benefits, such as water saving and air quality improvement, that are difficult or sometimes impossible to quantify. Including quantified estimates of these other benefits could significantly reduce the CCE for some measures (Worrell et al. 2003; Hasanbeigi et al. 2012a,b). Wächter (2013) discusses some of the advantages and limitations of CSC method.

[4] We listed 42 energy-efficiency measures in the questionnaire. However, we were only able to get information on penetration rates for 26 technologies. Thus, for this study, we used those 26 measures to analyze the energy-efficiency improvement potential in China's ammonia industry.

4.4 Co-benefits of energy-efficiency measures

To calculate the co-benefits of the reductions in both air-pollutant emissions and water use, we first estimated the emissions factors for fuel consumption and electricity generation. Then, we multiplied the fuel and electricity savings by these emissions factors to get the total emissions reductions for different air pollutants. The emissions reductions were calculated using Eq. (6); a similar approach was used to calculate water savings with Eq. (7). Tables 5 and Table 6 show the emissions and water consumption factors for fuel production and electricity generation.

$$ER = SF \times EF_1 + SE \times EF_2 \tag{6}$$

$$WS = SF \times WF_1 + SE \times WF_2 \tag{7}$$

ER = emissions reductions

SF = fuel savings (GJ)

EF_1 = emission coefficient of fuel (kg/GJ)

SE = electricity savings (KWh)

EF_2 = emission coefficient of electricity (kg/MWh)

WS = water savings (cubic meter [m^3])

WF_1 = water coefficient in fuel production (m^3/terajoule [TJ])

WF_2 = water coefficient in electricity generation (m^3/KWh).

Table 5. Emissions factors for fuel consumption and electricity generation (Zhao et al. 2012)

	Type	Unit	SO_2	NOx	PM_{10}
Chemical industry	Coal	Kg/GJ	0.605	0.191	0.077
	Coke	Kg/GJ	0.582	0.147	0.009
	Oil	Kg/GJ	0.063	0.250	0.009
	Natural gas	Kg/GJ	0.004	0.042	0.006
Electricity generation		Kg/MWh	2.360	2.260	0.390

Table 6. Summary of water consumption and withdrawal coefficients for fuel production and power generation processes in 2012

Type	Unit	Water withdrawal	Water consumption	Data source
Coal production	m^3/TJ	13.00	4.000	(Hejazi et al. 2014)
Coke production	m^3/TJ	0.07[a]	0.020	(Pan et al. 2012)
Natural gas production	m^3/TJ	0.03	0.010	(Li et al. 2012)
Crude oil production	m^3/TJ	145.00	44.000	(Hejazi et al. 2014)
Unconventional oil production	m^3/TJ	21.00	6.000	(Hejazi et al. 2014)
Thermal power	m^3/MWh	28.50	2.850	(Pan et al. 2012)
Nuclear power	m^3/MWh	9.80	2.600	(Li et al. 2012, McMahon 2011)
Wind power	m^3/MWh	0.20	0.004	(Li et al. 2012, Davis et al. 2013)
Solar photovoltaic power	m^3/MWh	0.10	0.100	(Davis et al. 2013)

5. Energy-efficiency measures for the ammonia industry

In this study, we analyzed 26 typical energy-efficiency measures applicable to China's ammonia industry. Table 7 presents the energy-savings, costs, and current adoption rate. The appendix to this report briefly describes each measure. The description or the main source for these technologies or measures can be found in the *National Extension Directory of Important Energy Conservation Technology* (NDRC 2008; 2009; 2011a,b; 2012; 2013) and in *The Advanced Technology Catalog of Energy Conservation and Emissions Reduction in the Petrochemical Industry* (MIIT 2012b).

Table 7. Typical energy savings and costs for energy-efficiency technologies and measures applied to the Chinese ammonia industry

No.	Energy-efficiency Technology/Measure[a]	Production in 2012 (Mt)[a]	Typical electricity savings (KWh/t product)[b]	Typical fuel savings (GJ/t product)[b]	Typical capital cost (RMB/t product)	Typical change in O&M cost (RMB/t product)	Potential adoption rate in 2012 (%)
Ammonia synthesis							
1	New catalyst for ammonia synthesis, e.g., ferrous-oxide-based	23.62	0	0.38	280.5	0	45%
2	Large-scale axial and radial ammonia synthesis tower	39.40	20.0	3.22	225.0	0	71%
3	JR type ammonia synthesis tower internals with multi-stage adiabatic heat-exchange system	47.81	73.3	0	165.0	0	56%
4	Unpowered ammonia-recovery technology	47.81	0	0.94	8.0	0	66%
5	Synthesis-gas molecular sieve dryer and direct synthesis converter feed	28.47	0	0.67	57.6	0	48%
6	Automatic control and optimization of ammonia synthesis reactor temperature	10.00	40.0	0.51	5.0	0	68%
Gas generation							
7	Three-waste fluidized-mix combustion furnace	36.34	0	2.32	65.0	0	49%
8	Heat recovery from re-former flue gas	36.34	0	0.17	3.5	0	30%
9	Low-energy natural-gas re-forming technology	10.52	-250.0[c]	3.31	1,100.0	0	65%
10	Adiabatic pre-re-former	47.81	58.10	0	67.7	0	66%
11	High-pressure coal-gasification	47.81	27.80	0	60.0	0	70%

12	Multi-nozzle opposed coal-water slurry gasification technology	36.34	0	6.44	925.0	0	46%
13	Pulverized coal pressure-gasification technology	36.34	0	6.44	900.0	0	47%
14	Slag and non-slag coal-water slurry gasification technology	36.34	0	6.44	800.0	0	47%
Gas purification							
15	Recovering waste heat from reformer flue gas	47.81	13.90	0.05	8.5	0	30%
16	CO_2 removal system using N-methyldiethanolamine (MDEA) solution	10.52	0	3.52	28.0	0	39%
17	Two-stage PSA (Pressure swing adsorption) CO_2 removal technology in ammonia synthesis plant	47.81	0	1.86	200.0	65	44%
18	Low-energy CO_2 removal technologies, e.g., NHD (Polyethylene Glycol Dimethyl Ether)	36.34	0	5.80	310.0	140	36%
19	Low-temperature methanol absorption technology (Rectisol)	37.29	0	0.57	370.0	120	51%
20	Full autothermic non-constant pressure methanolizing-methanation process	47.81	0	1.13	250.0	0	61%
21	Methanolization-hydrocarbylation purification technology	47.81	50.00	0.88	140.0	0	50%
Shift conversion							
22	All low-temperature conversion technologies	47.81	0	0.45	100.0	0	28%
23	Medium-low-low temperature conversion technology	36.34	0	1.50	60.0	0	46%

General Measures							
24	Combined-cycle technology	10.52	0	2.32	250.0	0	61%
25	Evaporative condenser cooling technology	47.81	25.00	0	15.0	0	43%
26	High-efficiency rotor technology	47.81	1.22	0	2.0	0	19%

[a] Main sources for ammonia production data: Han 2010, ERI 2013a, Jia et al. 2012, Gu 2013, IFA 2014.

[b] Main sources for specific technical data: CHO et al. 1997; Islam et al. 2005; Nand and Goswami 2008; NDRC 2008, 2009, 2011a&b, 2012, 2013; Wina et al. 2009; Zhang et al. 2012; Tong et al. 2012; MIIT 2012; ERI 2013a&b IETD 2014.

[c] A negative value for electricity savings indicates that although this measure saves fuel, it increases electricity consumption. However, the total final and primary energy savings of this measure is positive.

6. Results and discussion

Based on the methodology and the technological data, we constructed the fuel conservation supply curve (FCSC) and the electricity conservation supply curve (ECSC) to estimate the cost-effective and total technical potential for fuel- and electricity-efficiency improvements, respectively, in China's ammonia industry. Although the energy-saving potential would be realized during a future period of time, our analysis results highlight the total potential that exists in the industry; we do not assess how this potential will be realized in the future. Additionally, we estimate the air-pollutant emissions reductions and water savings from implementing these energy-efficiency measures, based on the fuel and electricity savings. Out of 26 measures that are applicable to China's ammonia industry, 20 were fuel-saving measures and were included in the FCSC, and 6 others were included in the ECSC.

The technologies and measures have varying impacts on fuel and electricity savings. For example, some technologies save only fuel or only electricity, some increase electricity consumption as a result of saving fuel, and some save both electricity and fuel. Examples of the latter include large-scale axial and radial ammonia synthesis tower, automatic control and optimization of ammonia synthesis reactor temperature, Recovering waste heat from reformer flue gas, and methanolization-hydrocarbylation purification technology. When a technology's fuel savings accounted for the larger portion of total primary energy savings, we included this technology only in the FCSC and not the ECSC.

6.1 Fuel CSC for China's ammonia industry

When the discount rate is 30%, the FCSC is as shown in Figure 6 where we see that 10 energy-efficiency measures (numbers 1-10 in Table 8) fall below the ammonia industry's 2012 average fuel price line (33.48 RMB/GJ). For these measures, the CCE_{fuel} is less than the average fuel price. The remaining 10 measures (numbers 11-20 in Table 8) have CCE_{fuel} higher than the average fuel price line, so, although they are technically applicable, they are not cost-effective.

Table 8 presents the fuel-efficiency measures applicable to China's ammonia industry, ranked by their CCEs. The table also shows the fuel savings and CO_2 emissions reductions from each measure. Automatic control and optimization of ammonia synthesis reactor temperature, low-energy CO_2 removal systems with N-methyldiethanolamine (MDEA), and the unpowered ammonia-recovery technology are the top three cost-effective measures. Furthermore, the high-pressure coal-gasification technology saves the most fuel of all of the energy-efficiency measures.

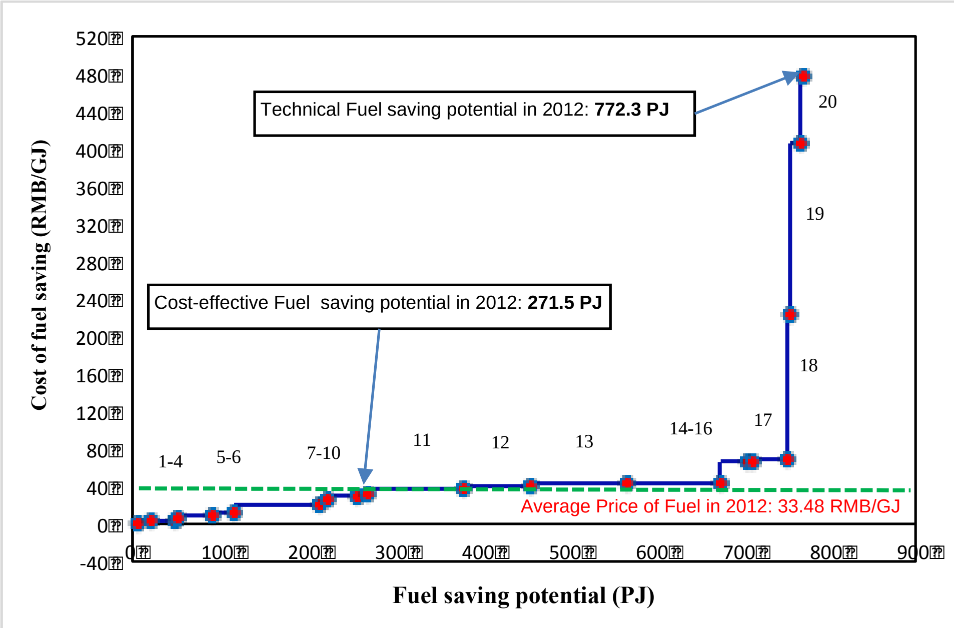

Figure 6. Fuel conservation supply curve (FCSC) for China's ammonia industry

Table 8. Fuel-efficient measures for China's ammonia industry, ranked by CCE_{fuel}

CCE_{fuel} rank	**Energy-Efficiency Technology/Measure**	**Fuel savings in petajoules (PJ)**	**CCE_{fuel} (RMB/GJ)**	**CO_2 mitigation (Mt CO_2)**
1	Automatic control and optimization of ammonia synthesis reactor temperature	6.3	1.6	0.5
2	CO_2 removal system using MDEA solution	14.2	2.4	1.2
3	Unpowered ammonia-recovery technology	29.4	2.6	2.5
4	Recovery of waste heat from re-former flue gas	1.8	6.2	0.2
5	Three-waste fluidized-mix combustion furnace	41.2	8.4	3.5
6	Medium-low-low temperature conversion technology	24.9	12.0	2.1
7	Large-scale axial and radial ammonia synthesis tower	96.3	19.8	8.0
8	Synthesis-gas molecular sieve dryer and direct synthesis converter feed	9.2	25.8	0.8
9	Methanolization-hydrocarbylation purification technology	33.2	30.1	2.7
10	Combined-cycle technology	14.8	32.5	1.2
11	Slag and non-slag coal-water slurry gasification technology	111.0	37.5	9.3

CCE_{fuel} rank	Energy-Efficiency Technology/Measure	Fuel savings in petajoules (PJ)	CCE_{fuel} (RMB/GJ)	CO_2 mitigation (Mt CO_2)
12	Low-energy CO_2 removal technologies, e.g., NHD (Polyethylene Glycol Dimethyl Ether)	75.2	40.3	6.3
13	High-pressure coal-gasification technology	110.8	42.2	9.3
14	Multi-nozzle coal-water mixture gasification technology	106.5	43.3	8.9
15	Automatic control and optimization of ammonia synthesis reactor temperature	32.8	66.8	2.7
16	All low-temperature conversion technologies	6.1	66.9	0.5
17	Two-stage PSA (Pressure swing adsorption) CO_2 removal technology in ammonia synthesis plant	38.9	67.5	3.3
18	New catalyst for ammonia synthesis, e.g., ferrous-oxide-based	4.0	223.8	0.3
19	Low-temperature methanol absorption technology (Rectisol)	10.9	406.3	0.9
20	Low-energy natural-gas re-forming technology	4.8	477.6	0.6

The cost-effective fuel-efficiency improvement potential for China's ammonia industry in 2012 is 271.5 petajoules (PJ), equal to approximately 14% of the industry's total fuel use in that year. The total technical fuel-savings potential is 772.3 PJ, equal to approximately 40% of the Chinese ammonia industry's total fuel consumption in 2012 (Table 9). The CO_2 emissions reduction associated with the cost-effective savings potential is 22.5 Mt CO_2, and the total CO_2 emissions reduction associated with the technical fuel-savings potential is 64.7 Mt CO_2. As Table 8 shows, the cost-effective and technical potentials for CO_2 emissions reductions are equal to 12% and 34%, respectively, of the total CO_2 emissions from China's ammonia industry in 2012.

Table 9. Fuel savings and CO_2 mitigations for China's ammonia industry

	Fuel savings (PJ)		CO_2 mitigation (Mt CO_2)	
	Cost-effective	Technical	Cost-effective	Technical
Savings potential for 2012	271.5	772.3	22.5	64.7
Share of China's ammonia industry fuel use and total CO_2 emissions in 2012	14%	40%	12%	34%

6.2 Electricity CSC for China's Ammonia Industry

When the discount rate is 30%, the ECSC is as shown in Figure 7. Six energy-efficiency measures were included in the ECSC. Figure 7 and Table 10 show that all six electricity-efficiency measures fell under the average electricity price line (760 RMB/MWh) for the ammonia industry in 2012. Therefore, for these measures, the $CCE_{electricity}$ was less than the average unit price of electricity, and these measures can be considered cost-effective.

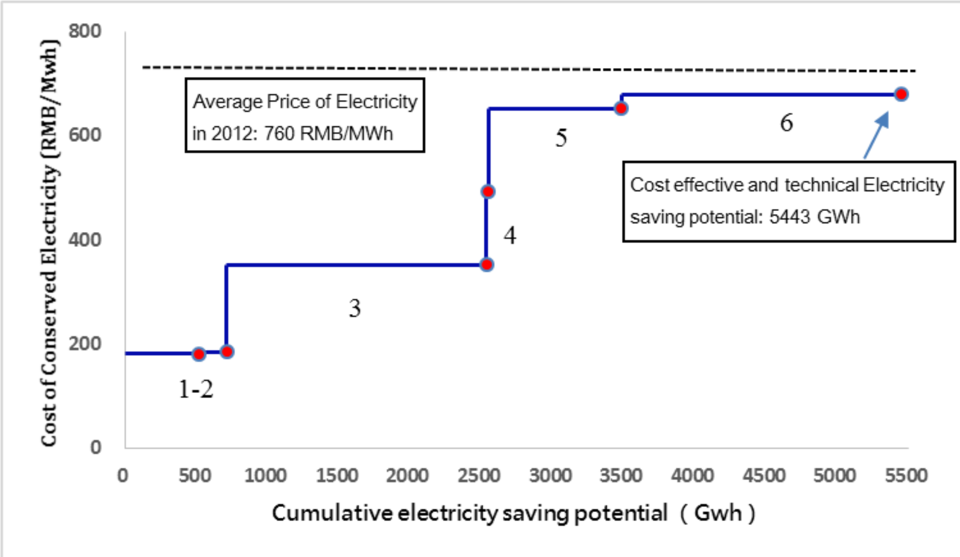

Figure 7. Electricity conservation supply curve (ECSC) for China's ammonia industry

Table 10 shows all of the electricity-efficiency measures applicable to China's ammonia industry, ranked by CCE, as well as the electricity savings and CO_2 emissions reductions from each measure. Among the electricity-efficiency measures, the top three cost-effective measures are evaporative condenser cooling technology, Recovering waste heat from reformer flue gas, and use of an adiabatic pre-re-former.

Table 10. Electricity-efficiency measures for China's ammonia industry, ranked by $CCE_{electricity}$

$CCE_{electricity}$ Rank	**Energy-Efficiency Technology/Measure**	**Electricity savings (GWh)**	**$CCE_{electricity}$ (RMB/MWh)**	**CO_2 mitigation (Mt CO_2)**
1	Evaporative condenser cooling technology	516	181.0	0.40
2	Recovering waste heat from reformer flue gas	197	184.6	0.15
3	Use of an adiabatic pre-re-former	1,822	351.4	1.41
4	High-efficiency rotor technology	11	492.5	0.01
5	High-pressure coal-gasification technology	935	651.4	0.72
6	JR type ammonia synthesis tower internals with multi-stage adiabatic heat-exchange system	1,961	679.3	1.52

The total electricity-efficiency improvement potential for China's ammonia industry in 2012 is 5,443 GWh or approximately 14% of the industry's total electricity use in 2012. Especially interesting is that all of the electricity-efficiency improvement potential is cost-effective (Figure 7). The CO_2 emissions reduction associated with the total electricity savings potential is 4.2 Mt CO_2. As Table 10 shows, the cost-effective and technical potential for CO_2 emissions reduction represents approximately 2% of the industry's total CO_2 emissions in 2012.

Table 11. Annual electricity savings and CO_2 mitigations for China's ammonia industry

	Electricity savings (GWh)		**CO_2 mitigation (Mt CO_2)**	
	Cost-effective	**Technical**	**Cost-effective**	**Technical**
Savings potential for 2012	5,443	5,443	4.2	4.2
Share of China's ammonia industry electricity use and total CO_2 emissions in 2012	14%	14%	2%	2%

6.3 Total energy-saving potential for China's ammonia industry

6.3.1 Final energy-saving potential

Table 12 shows the total final energy-savings and total CO_2 emissions reductions for China's ammonia industry from all of the applicable fuel- and electricity-saving measures presented above. The cost-effective and technical final energy-savings potentials are equal to 14% and 38%, respectively, of the final energy consumption of the industry in 2012. Total technical CO_2 reduction potential associated with the energy-efficiency measures studied here is 26.8 Mt CO_2, which is equal to approximately 14% of the total CO_2 emissions of China's ammonia industry in 2012. Of the total technical final energy-savings potential, 36% is cost-effective, but these measures have not been adopted by the industry for financial, technical, or other reasons. It is important to understand and address these reasons; this could be a good topic for future studies.

Table 12. Final energy-savings and CO_2 mitigation potential for China's ammonia industry

	Final energy-savings potential (PJ)		**CO_2 mitigation potential (Mt CO_2)**	
	Cost-effective	**Technical**	**Cost-effective**	**Technical**
Savings potential for 2012	291.1	791.9	26.8	68.9
Share of China's ammonia industry in 2012	14%	38%	14%	36%

6.3.2 Primary energy saving potential

We used a factor of 2.9 to convert the electricity-savings potentials to primary energy for the year 2012 in China. This takes into account the average efficiency of power generation (0.333 Kgce/KWh) as well as transmission and distribution losses (6.74%) in that year (China Power Yearbook, 2013). Table 13 shows the total primary energy savings and CO_2 emissions reduction potentials from all applicable electricity and fuel-saving measures presented in Sections 5. The primary cost-effective and technical energy-savings potentials are 328.4 PJ and 829.2 PJ, respectively, representing 14% and 35% of the total primary energy use in China's ammonia industry in 2012.

Table 13. Primary energy-savings and CO_2 mitigation potential for China's ammonia industry

	Primary energy-savings potential (PJ)		**CO_2 mitigation potential (Mt CO_2)**	
	Cost-effective	**Technical**	**Cost-effective**	**Technical**
Savings potential for 2012	328.4	829.2	26.8	68.9
Share of China's ammonia in 2012	14%	35%	14%	36%

6.4 Co-benefits analysis

6.4.1 Air-pollutant emissions reduction

We used the SO_2, NOx, and PM_{10} emission factors for fuels as well as grid electricity and multiplied these factors by fuel- and electricity-saving potential, respectively, to assess the potential reduction in air pollutants. Table 14 shows the air-pollutant reduction potential from the 26 energy-efficiency measures analyzed in this study.

Table 14. Annual air pollutant mitigation potential for China's ammonia industry

	SO_2（Kilotons [kt]）		NOx (Kt)		PM_{10} (Kt)	
	Cost-effective	Technical	Cost-effective	Technical	Cost-effective	Technical
Emissions reduction from fuel savings	85.2	242.4	33.9	96.4	39.4	111.9
Emissions reduction from electricity savings	8.7	8.7	11.1	11.1	2.4	2.4
Total emissions reduction	93.9	251.1	45.0	107.5	41.8	114.3
Share of Chinese ammonia industry's emissions in 2012	7%	20%	9%	21%	7%	20%

6.4.2 Water savings

We estimated the reduction in water consumption and withdrawal from the energy-efficiency measures by multiplying fuel and electricity savings by water coefficients for fuel production and electricity generation, given in Section 4. The results are shown in Table 15. The total technical reduction in water withdrawal from implementation of all of the energy-efficiency measures studied is equal to 142.5 million m^3, which is approximately 11% of total water withdrawal in China's ammonia industry in 2010 (MIIT 2012a). Figure 8 compares the reduction in water withdrawal from the energy-efficiency measures with the residential water withdrawal in China's Hainan province and in the city of Tianjin in 2012. The water savings in the ammonia industry is equal to approximately 22% of the residential water withdrawal in Hainan province (which has a population of 8.9 million) and to 28% of residential water withdrawal in Tianjin City (which has a population of 14.1 million) in 2012 (NBS 2013).

Table 15. Annual water consumption and withdrawal reduction potential as co-benefits of energy-efficiency measures in 2012

	Water consumption (1,000 m^3)		Water withdrawal (1,000 m^3)	
	Cost-effective	Technical	Cost-effective	Technical
Water savings as co-benefits of fuel-savings potential	4,784	13,610	15,743	44,788
Water savings as co-benefits of electricity-savings potential	10,134	10,134	97,734	97,734
Water savings as co-benefits of total savings potential	14,918	23,744	113,477	142,522

6.5 Sensitivity analysis

We performed sensitivity analyses to assess the influence of the following five parameters on the energy-efficiency potentials and cost-effectiveness results: adoption rate, discount rate, electricity and fuel prices, investment costs, and energy savings from the energy-efficiency measures.

6.5.1 Adoption rate

Cost-effective and technical energy savings are directly related to the adoption rate of each measure in the ammonia industry. We tested four cases: ±10% and ±20% in adoption rate. Table 16 shows how changes in the adoption rate influence the cost-effective energy savings and their associated CO_2 emissions reductions. For fuel-saving measures, the cost-effective energy-savings potential might increase from 217.2 to 325.8 PJ when the adoption rate increases from -20% to

+20%, with associated cost-effective CO_2 reduction potential changes. However, the CCE_{fuel} does not change when the adoption rate changes. The cost-effective electricity savings might increase from 4,354 to 6,531 GWh when the adoption rate increases from -20% to +20%. From this, we can see that the adoption rate of each energy-efficiency measure has a significant impact on the total energy-saving and CO_2 reduction potentials.

Table 16. The annual cost-effective fuel- and electricity-savings potentials and CO_2 emissions reductions with different adoption rates

	Fuel			Electricity		
Adoption rate (%)	**Cost-effective savings (PJ)**	**Cost-effective CO_2 mitigation (Mt CO_2)**	**Cumulative CCE_{fuel} (RMB/GJ)**	**Cost-effective savings (GWh)**	**Cost-effective CO_2 mitigation (Mt CO_2)**	**Cumulative $CCE_{electricity}$ (RMB/MWh)**
-20%	217.2	18.0	43.6	4,354	3.4	499.2
-10%	244.3	20.3	43.6	4,899	3.8	499.2
BC**	271.5	22.5	43.6	5,443	4.2	499.2
+10%	298.6	24.8	43.6	5,987	4.6	499.2
+20%	325.8	27.1	43.6	6,531	5.1	499.2

* Cumulative CCE_{fuel} (the sum of CCEs of all 20 applicable fuel-saving measures) and $CCE_{electricity}$ (the sum of CCEs for all 6 applicable electricity-saving measures) are presented as indicators to show that the change in adoption rate will affect the cost-effective energy savings and CO_2 mitigation.
** "BC" is the base-case scenario used in the main analysis presented in this report.

6.5.2 Discount rate

Decreasing the discount rate reduces the CCE, which could increase the cost-effective energy-savings potentials, depending on the energy price. Therefore, we conducted a sensitivity analysis using discount rates of 5%, 15%, 25%, 30%, and 40% to assess the effect of changing the discount rate on the CCE and cost-effective energy savings. From Table 17, we can see that reducing the discount rate from 30% to 5% will increase the cost-effective fuel-saving potential from 271.5 to 685.0 PJ while the cost-effective electricity-savings potential (5,443 GWh) does not change when the discount rate varies within the range studied. The reason is that the total electricity savings in the ECSC are already extremely cost effective, so changes in the discount rate between 5% and 30% do not influence its cost-effectiveness.

The cost-effectiveness of the savings might not change when the discount rate varies because energy prices also play a role in determining cost-effectiveness (as is the case for cost-effective electricity savings when the discount rate varies from 40% to 5%). The cumulative CCE_{fuel} decrease with a decline in the discount rate regardless of the cost-effectiveness. The total technical energy-savings potentials do not change with a decline in the discount rate, but CCE_{fuel} and $CCE_{electricity}$ lower than those we analyzed could affect these potentials.

Table 17. Sensitivity analysis for the annual cost-effective fuel- and electricity-savings potentials and CO_2 emissions reductions with different discount rates

Discount rate (%)	Fuel			Electricity		
	Cost-effective savings (PJ)	**Cost-effective CO_2 mitigation (Mt CO_2)**	**Cumulative CCE_{fuel} (RMB/GJ)**	**Cost-effective savings (GWh)**	**Cost-effective CO_2 mitigation (Mt CO_2)**	**Cumulative $CCE_{electricity}$ (US$/MWh)**
5%	685.0	59.6	16.8	5,443	4.2	132.8
15%	675.0	56.4	26.4	5,443	4.2	264.5
25%	382.5	31.8	37.7	5,443	4.2	418.6
30%**	271.5	22.5	43.6	5,443	4.2	499.2
40%	214.2	17.9	55.6	2,546	2.0	662.9

* Cumulative CCE_{fuel} (the sum of CCEs of all 20 applicable fuel-saving measures) and $CCE_{electricity}$ (the sum of CCEs for all six applicable electricity-saving measures) are presented as indicators to show that although a change in discount rate might not result in a change in cost-effective savings and CO_2 emissions reduction, the change in discount rate will change the CCE in general.
** 30% of the discount rate is the base-case scenario used in the main analysis presented in this report.

6.5.3 Energy price

The energy price can directly influence the cost-effectiveness of energy savings. A higher energy price could result in more energy-efficiency measures being cost effective and could increase the number of instances in which the CCE falls below the energy price line on the CSC. We conducted a sensitivity analysis of the impact of changing electricity and fuel prices by assuming 10%, 20%, and 30% increases in energy prices as well as a 10% decrease in energy prices (we considered multiple potential increases but only one decrease because energy prices are more likely to increase than to decrease). Because coal prices vary in different regions of China, this sensitivity analysis is especially important for the FCSC.

Table 18 shows how the cost-effective energy savings and their associated CO_2 emissions reductions change with changes in energy prices while other parameters (adoption rate, discount rate, investment costs of measures, and energy savings from measures) are held constant. For fuel-conservation measures, the cost-effective energy-savings potentials do not change with a 30% reduction in fuel price. This is because a change of fuel price in this range does not change the positions of the CCE_{fuel} of the measures relative to the fuel price line. In other words, the ranking of the measures in relation to the average fuel price line does not change.

An increase in electricity price does not change the cost-effective electricity-savings potential. Similarly, a reduction of up to 70% in the average electricity price does not change the cost-effective electricity-savings potential because a change in the average electricity price in this range does not change the positions of the CCEs of the measures compared to the electricity price line. That is, no measures will move up to the average electricity price line as a result of this price change. The total technical energy-savings and CO_2 mitigation potentials do not change with variation in energy prices.

Table 18. Sensitivity analysis for annual cost-effective fuel- and electricity-savings potentials and CO_2 emissions reductions with different energy prices

Energy price	Fuel			Electricity		
	Fuel price (RMB/GJ)	Cost-effective savings (PJ)	Cost-effective CO_2 mitigation (Mt CO_2)	Electricity price (RMB/MWh)	Cost-effective savings (GWh)	Cost-effective CO_2 mitigation (Mt CO_2)
-10%	30.13	256.6	21.3	684.0	5,443	4.2
BC energy price*	33.48	271.5	22.5	760.0	5,443	4.2
+10%	36.83	271.5	22.5	836.0	5,443	4.2
+20%	40.18	382.5	31.8	912.0	5,443	4.2
+30%	43.52	675.0	56.4	988.0	5,443	4.2

* The base-case energy prices are those used in the main analysis presented in this report.

6.5.4 Investment costs/energy savings

Variations in the investment-cost and energy-savings assumptions for each energy-efficiency measure will also change the results. A change in either the investment costs or the energy savings of the measures will directly change the CCE (Equation 4). If the change in the investment costs or/and the energy savings is large enough to change the position of the CCE of any energy-efficiency measure relative to the energy price line in the CSC (for example, to bring it below the line if it was above the energy line before the change, or vice versa), then it will change the cost-effective energy-savings potential. Furthermore, a change in the energy savings of any measure will change the total amount of energy-savings potential regardless of the measure's cost-effectiveness.

Therefore, we performed sensitivity analysis for changes in investment costs and energy savings for each measure (shown in Tables 19 and 20, respectively) to assess the impact of these changes on the results. We analyzed four cases: a 10% and 20% increase in investment costs or energy savings and a 10% and 20% decrease.

As noted above, in reality, the energy-savings potentials and investment costs of each energy-efficiency measure and technology may vary and will depend on factors such as raw materials, technology provider, production capacity, installation size, final product quality, and time of the analysis. Thus, we performed sensitivity analyses to assess the effect of changes in investment costs and energy savings of each measure on the final results.

Equation 4 shows that the CCE is directly related to the investment costs and has an inverse relation to the energy savings of the measures. However, the cost-effective energy-savings potential changes only if a change in investment costs and/or energy savings is large enough to change the position of the CCE of any energy-efficiency measure relative to the energy price line in the CSC (e.g., to bring a measure's CCE below the line if it was above the line before the change, or vice versa). In addition, the change in energy savings of any measure changes the total energy-savings potential regardless of the measure's cost-effectiveness.

Tables 19 and 20 show how changes in the investment costs and energy savings of the measures can affect the cost-effective energy-savings potentials and their associated CO_2 emissions reduction potentials, respectively, while the other parameters are held constant.

Table 19 shows that the cost-effective fuel- and electricity-savings potential and associated CO_2 reductions do not change when the investment costs of the energy-efficiency technologies change by +/-20%. This is because the variation in the investment cost does not change the position of the CCEs relative to the energy price line in the CSC. Table 19 also shows that although the cost-effective energy-savings potential does not change when the investment cost varies in the above range, the cumulative CCE declines with a decrease in investment cost of the technologies. That is to say that the energy-savings potential can be achieved at lower costs if the investment cost of the technologies decreases. The total technical energy-savings and CO_2 mitigation potentials do not change when investment costs vary.

Table 19. Sensitivity analysis for annual cost-effective fuel- and electricity-savings potentials and CO_2 emissions reductions with different investment costs of measures

Investment cost (%)	**Fuel**			**Electricity**		
	Cost-effective savings (PJ)	**Cost-effective CO_2 mitigation (Mt CO_2)**	**Cumulative CCE_{fuel} (RMB/GJ)**	**Cost-effective savings (GWh)**	**Cost-effective CO_2 mitigation (Mt CO_2)**	**Cumulative $CCE_{electricity}$ (RMB/MWh)**
-20%	382.5	31.8	36.3	5,443	4.2	399.4
-10%	271.5	22.5	40.0	5,443	4.2	449.3
BC IC**	271.5	22.5	43.6	5,443	4.2	499.2
+10%	256.6	21.3	47.3	5,443	4.2	549.1
+20%	223.4	18.6	50.9	2,546	2.0	599.0

* Cumulative CCE_{fuel} (the sum of the CCEs of all 20 applicable fuel-saving measures) and $CCE_{electricity}$ (the sum of the CCEs for all six applicable electricity-saving measures) are presented as indicators to show that although the change in investment costs may not result in a change in cost-effective savings and CO_2 emissions reduction, it will change the CCE in general.

** The base-case investment costs used in the main analysis presented in this report.

Table 20. Sensitivity analysis for annual cost-effective fuel- and electricity-savings potentials and CO_2 emissions reductions with different energy savings of measures

Energy savings (%)	Fuel				Electricity			
	Cost-effective savings (PJ)	Cost-effective CO_2 mitigation (Mt CO_2)	Cumulative CCE_{fuel} (US$/GJ saved)	Total fuel savings (PJ)**	Cost-effective savings (GWh)	Cost-effective CO_2 mitigation (Mt CO_2)	Cumulative $CCE_{electricity}$ (US$/GWh saved)	Total electricity savings (GWh)**
-20%	178.7	14.9	54.5	617.9	2,037	1.6	624.0	4,354
-10%	231.0	19.2	48.5	695.1	4,898	3.8	554.7	4,898
BC**	271.5	22.5	43.6	772.3	5,443	4.2	499.2	5,443
+10%	298.6	24.8	39.6	849.6	5,987	4.6	453.8	5,987
+20%	459.0	38.2	36.3	926.8	6,531	5.1	416.0	6,531

* Cumulative CCE_{fuel} (the sum of the CCE_{fuel} of all 20 applicable fuel-saving measures) and cumulative $CCE_{electricity}$ (the sum of the $CCE_{electricity}$ of all give applicable electricity-saving measures) are presented as indicators to show that although a change in energy savings may not result in a change in cost-effective savings and CO_2 emissions reduction, it will change the CCE in general.
** The base-case energy savings used in the main analysis presented in this report.

Table 20 shows how the cost-effective fuel-savings potential increases from 178.7 PJ to 459.0 PJ and the cost-effective electricity-savings potential increases from 4,354 GWh to 6,531 GWh as a result of a change in energy savings from -20% to+20%. That is, even greater energy savings can be achieved than indicated by the CSC analysis, depending on the current efficiency of a plant and the degree of efficiency that a specific technology can attain. Furthermore, the cumulative CCE_{fuel} and $CCE_{electricity}$ decrease in accordance with the increase in energy savings of each technology. The total technical energy- (electricity and fuel) savings potentials also increase as the energy savings of each measure increase (see Table 20).

7. Summary and conclusions

This study used a bottom-up approach for quantifying the energy-saving and emission-reduction potentials for 26 technologies and measures in China's ammonia industry. The ammonia industry is one of the most energy-intensive industries in China, emitting CO_2 and air pollutants. The Chinese ammonia industry's annual cost-effective fuel-saving potential is estimated to be 271.5 PJ, and the annual technical fuel-saving potential is 772.3 PJ, which are equal to 14% and 40%, respectively, of the total fuel consumption in China's ammonia industry in 2012. The cost-effective and total technical CO_2 emissions-reduction potentials associated with the fuel savings are 22.5 and 64.7 Mt CO_2, respectively, equal to 12% and 34% of the total CO_2 emissions from China's ammonia industry in 2012. The total annual electricity-efficiency potential is 5,443 GWh, which is equal to 14% of the Chinese ammonia industry's total electricity use in 2012. All of the electricity-efficiency potential is found to be cost effective, with associated CO_2 emissions reductions of 4.2 Mt CO_2.

We also quantified the co-benefits of air-pollutant emissions reductions and water savings that would result from adopting energy-efficiency measures in China's ammonia industry. The air pollutant reduction potentials associated with the cost-effective and technical fuel savings are 85.2 and 242.4 Kt SO_2, 33.9 and 96.4 Kt NOx, 39.4 and 111.9 Kt PM_{10}, respectively. The air-pollutant reduction potentials associated with the electricity-saving measures are 8.7 Kt SO_2, 11.1 Kt NOx, and 2.43 Kt PM_{10}. The total technical reduction in water withdrawal from implementation of all the 26 energy-efficiency measures studied is equal to 142.5 million m^3, which is approximately 11% of total water withdrawal by China's ammonia industry (1,270 million m^3) in 2012.

The results of sensitivity analyses show that adoption rate has a significant influence on the cost-effective energy- and electricity-savings potential from the efficiency measures as well as on the technical energy-savings potential. The cost-effective energy-savings and CO_2 reductions potential will not change if there are limited changes in energy prices. Variations in the discount rate strongly affect the cost-effective fuel savings, but the cost-effective electricity savings do not change with changes in the discount rate within the specified range.

The approach used in this study should be viewed as a screening tool to assist policymakers in assessing the benefits of energy-saving and CO_2-mitigation measures when designing appropriate sector-specific energy-efficiency policies. The fuel CSC shows that automatic control and optimization of ammonia synthesis reactor temperature, low-energy CO_2 removal systems with MDEA, and unpowered ammonia-recovery technology are three of the most promising fuel-saving technologies because they are both cost effective and save significant energy. Three promising electricity-savings technologies, based on the criteria of cost-effectiveness and high energy-saving potential, are evaporative condenser cooling technology, recovery of waste heat from flue gas in gas purification, and use of an adiabatic pre-re-former.

Our results emphasize the importance of energy-efficiency measures and point to unrealized energy savings and CO_2-mitigation potential in energy-intensive industries. However, an "efficiency gap" remains in the ammonia industry because many of the identified cost-effective opportunities still have not been adopted. This "efficiency gap" persists because of barriers to adoption of these efficiency measures. Thus, providing information is an important first step; it is then up to policy makers to ensure that the results are disseminated and transformed into enforceable policies, and to provide financial support to promote the implementation of energy-efficiency measures.

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Appendix: Description of energy-efficiency measures for the ammonia industry

EE-1: New catalyst for ammonia synthesis, e.g., ferrous-oxide-based

The ferrous-oxide-based catalyst is highly active in catalyzing nitrogen and hydrogenate to synthesize ammonia. The catalyst is prepared by a melting method and can be used in ammonia-synthesizing devices of various sizes. It is particularly suitable for low-pressure, low-energy-consumption ammonia synthesis. Use of this catalyst saves energy, improves efficiency, and reduces the cost of the process (Bencic 2001, Xu 2006, MIIT 2012b).

EE-2: Large-scale axial and radial ammonia synthesis tower

The structure of the ammonia synthesis tower is very important to the ammonia-production facility's energy-efficiency and production capacity. In conventional shift converter designs, the process gas travels axially through the catalyst bed whereas in axial-radial flow converters, the process gas travels axially and radially through the catalyst bed. The axial and radial gas flow in an axial-radial flow reactor used for ammonia synthesis can reduce the resistance and energy consumption of the process compared to the performance of a conventional axial or radial reactor. Use of an axial-radial flow reactor increases conversion efficiency and reduces pressure drops in the process. This measure is applicable to all types of feedstocks and to both carbon monoxide (CO) shift converters and ammonia synthesis converters (Cui 1994, Xu et al. 2002, MIIT 2012b, IETD 2014).

EE-3: JR type ammonia synthesis tower internals with multi-stage adiabatic heat-exchange system

A unique heat-exchange technology and multi-adiabatic system can be applied in the ammonia synthesis tower. This technology promotes catalytic reactions among different stages in an adiabatic catalytic bed and cools the reaction gas separately to promote reactions following an optimum temperature curve. Thus, this technology makes full use of the synthesis catalyst and decreases energy consumption (Jin 1996, MIIT 2012b).

EE-4: Unpowered ammonia-recovery technology

An ammonia recovery system that does not require additional power can be used to extract ammonia from the facility's purge (vent) gas. This recovered ammonia can be sold or used directly in urea production, creating value for the purge gas ammonia and solving a critical problem of large quantities of dilute aqua ammonia, which are difficult to deal with. Recovering this ammonia avoids consumption of additional water and energy (Yu 2009).

EE-5: Synthesis-gas molecular sieve dryer and direct synthesis converter feed

With the use of molecular sieve adsorbers serving as dryers, the make-up gas stream can be completely freed of water and carbon oxides prior to its entrance in the ammonia synthesis reactor. The make-up gas can then be directly fed to the synthesis reactor. The conversion rate is improved due to the lower ammonia content in the gas entering the reactor. The improved conversion will reduce the energy requirements for recycling non-activated gas and potentially reduce the loop operating pressure and thus, reduce the power requirements for compression. (Ullmann's Encyclopedia of Industrial Chemistry 2011, IETD 2014).

EE-6: Automatic control and optimization of ammonia synthesis reactor temperature

From a thermodynamic perspective, it is wasteful for high-temperature (~1000℃) gases to exit the secondary and primary re-formers just for producing steam. It is more efficient to utilize the heat from the secondary re-former gases in a new type of primary re-former, the heat exchanger re-former. This eliminates the use of the traditionally fuel-fired re-former furnace. When a heat exchanger is used, more oxygen needs to be supplied to the secondary re-former to increase the firing. Several processes operate without a fired primary re-former in an advanced configuration such as the ICI LCA and the KBR KAAP-plus processes. Other characteristics of these advanced processes are isothermal shift conversion, high-activity synthesis catalysts, and CO_2 removal systems with solid absorbent. In the KBR Re-forming Exchanger System (KRES) process, the natural gas stream is split into two after the de-sulfurization unit. The smaller of the two streams enters the heat exchanger and the other enters an autothermal re-former. The LCA and the KAAP-plus processes drastically decrease CO_2 emissions because they eliminate the flue gases from the primary re-former. These processes can also decrease NOx emissions by 50% or more (Ullmann's Encyclopedia of Industrial Chemistry 2011, IETD 2014).

EE-7: Three-waste fluidized-mix combustion furnace

The fluidized mix system provides a combustion furnace that can make stable use of three wastes (waste gas, waste residue, and waste ash of synthesis ammonia). The system is composed of a furnace body and a circulating fluidized device. The furnace can burn the three wastes simultaneously and can also be used for burning separated gas or coal. This system can reduce capital costs and energy consumption. (Peng 2001, Zhang et al. 2012, MIIT 2012b).

EE-8: Heat recovery from reformer flue gas

In this heat-recovery system, low-grade heat from the reformer flue gases can be recovered and used to preheat combustion air, producing low-pressure steam. It can also be used to preheat boiler feed water or demineralized water. For this system, additional heat recovery surface area is installed in the convection zone of the re-former furnace. The energy recovered from the re-former flue gas can reduce fuel consumption in the primary re-former. In plants designed with heat-recovery systems, heat-recovery efficiency can deteriorate over time, increasing the temperature of flue gases. In those cases, it is beneficial to replace the older heat-recovery systems with newer and more efficient systems (Christensen 2001, Nand and Goswami 2009, FAI 2013, IETD 2014).

EE-9: Low-energy natural-gas re-forming technology

This technology include two kinds of re-forming systems: heat-exchange and two-stage. Heat-exchange re-forming makes full use of the reaction heat from the second stage of the conversion furnace. This technology uses the conversion gas from the second furnace to heat the first-stage conversion furnace. For the two-stage re-forming system, the heat-exchange re-former and the box-type re-former are paralleled at the first stage of the conversion furnace; the second stage is the autothermal re-former. Both of these re-forming systems can reduce natural gas consumption (MIIT 2012b, China Environment Energy Capital Exchange 2013).

EE-10: Using an adiabatic pre-re-former

An adiabatic pre-re-former employs a highly active nickel catalyst to partially re-form a de-sulfurized hydrocarbon feed, using waste heat (480°C) from the convection section of the re-former. The use of waste heat lowers the steam consumption from the convection section of the re-former furnace, reducing the primary re-former duty and thereby reducing gas consumption. In addition to reducing energy consumption, use of a pre-re-former allows the primary re-former to be up to 25% smaller. This technology can also increase the production capacity without additional energy costs. Installing a pre-re-former at an existing plant will typically increase production by 10-20%. Other benefits of this technology include increased flexibility in feedstock going to the steam re-former and increased lifetime of the steam re-former and shift catalysts because almost all sulphur in the hydrocarbon feed and process steam is absorbed by the pre-re-forming catalyst. One disadvantage is that this technology requires an additional vessel, which will increase the pressure drop. This technology is applicable to older plants with excess steam production. Addition of pre-re-former in existing plants for the purpose of energy saving only might not be feasible from a technical or economic perspective (FAI 2013, IETD 2014).

EE-11: High-pressure coal-gasification technology

Preheated feedstock and high-pressure steam (3-4 megapascals) enter at the top of the primary re-former. Re-former pressure can be optimized by determining how close it is to the relief-valve design capability and increasing it where feasible. With older equipment, relief valves can be retrofitted to allow for higher pressure settings if they are safe for the equipment. Increasing the re-former pressure reduces the need for compression at the synthesis-gas compressor, which, in turn, reduces the steam used in steam-driven compressor units. As a result, more steam is available to other units. Fuel is saved in the balancing (external boilers) (IETD 2014).

EE-12: Multi-nozzle opposed coal-water slurry gasification technology

In this system, the gasification furnace assembly comprises the housing, the upper nozzle, and the surrounding nozzle. Advantages include: the upper and surrounding nozzles can produce impinging stream in the gasifier, the fluid flow behavior and flow structure are conducive to atomization and dispersion, the mixture is strengthened, and the heat and mass-transfer rate is improved, which extending the average residence time of raw material particles. This significantly improves the effect of gasification, enhances the carbon conversion rate, reduces the ash content in the fuel, and increases the air volume per unit of raw materials (Yu et al. 2001).

EE-13: Pulverized coal pressure-gasification technology

This technology uses high-temperature inert gas to dry the pulverized coal and transport the coal to the pulverized coal pipe in the gasifier burner. Then a mixture of steam and preheated O_2 is fed into the burner. An oxidation reaction takes place between the pulverized coal and the gas mixture in the furnace (Zhang 2007, MIIT 2012b).

EE-14: Slag and non-slag coal-water slurry gasification technology

This technology entails grading injection of oxygen to the gasification furnace. Most of the oxygen is injected from the top burner, but some is injected from the sidewall burner. Combustion from the sidewall burner can reduce the intensity of use of the main top burner, which can lead to continuous extension of the burner running time (Han 2009, MIIT 2012b).

EE-15: Recovering waste heat from flue gas in gasification

The technology recovers CO_2 from the flue gas using a combined method of membrane separation and chemical adsorption. It can also deeply cool, distill, and recovering argon gas in purge gas of a hydrogen-recovery device . And it can recycle a large quantity of low-temperature waste heat at the outlet position of the top of a regenerating tower. An ice engine is recycled using heat-pump technology. This saves the cold from the ice engine and pre-heating boiler water (Fu 2012, MIIT 2012b).

EE-16: CO_2 removal system use MDEA solution

Generic N-methyldiethanolamine (MDEA) is commonly used as a highly selective solvent to treat sour gases down to parts-per-million levels of hydrogen sulfide (H_2S) while slipping a large proportion of the CO_2 in the feed gas from the system. MDEA is also a major constituent in many specialty amine formulations developed for deeper CO_2 removal in applications such as synthesis gas production and treating high-CO_2 natural gases found in several regions of the world. In recent years, attempts have been made to use solvents containing MDEA alone for CO_2 removal from high-concentration gases, usually at high pressure (Seagraves 2009).

EE-17: Two-stage PSA (Pressure swing adsorption) carbon dioxide removal technology

Absorbents have different adsorption capacity, rate, and force at different pressures. At the first-stage with higher pressure, absorbents can remove impurities and have purified CO_2 (≥98.5%); while at the second stage with lower pressure, the absorbents can be further recovered from impurities. Thus, by using several adsorption beds, the adsorption pressure can be continuously changed to separate the gas mixtures (Song 2003).

EE-18: Low-energy carbon dioxide removal technology, such as NHD (Polyethylene Glycol Dimethyl Ether)

The NHD technology for desulfurization and CO_2 removal uses a small amount of energy consumption, produces a high degree of purification, entails simple equipment and process flow, and has been used successfully in desulfurization and CO_2 removal in ammonia and methanol manufacturing (Chen and Li 2008).

EE-19: Low-temperature methanol absorption technology (Rectisol)

The low-temperature methanol adsorption technology (Rectisol) has many advantages in gas purification. Methanol is used as the absorbent. Under low temperature, most of the acid gases (e.g., CO_2, hydrogen sulfide, and carbonyl sulfide) are highly soluble in methanol, so methanol cam be used remove these gases all simultaneously or one at a time (Kang and Tang 1999, Zhao , Wang et al. 2012).

EE-20: Full autothermic non-constant pressure methanolizing-methanation process

In carbon removal systems, a methanolizing device is installed at the medium-pressure compressor outlet, transforming most of the CO and CO_2 to methanol. Addition of a methanolizing device and methanation device to the high-pressure compressor outlet transforms the rest of the CO and CO_2 to methanol and methane. The reaction heat for the methanolizing-methanation process can be supplied from the synthesis reaction, reducing electricity consumption and cost (Shang 2005, Gu and Lian 2007, Zhang et al. 2012).

EE-21: Methanolization-hydrocarbylation purification technology

In this technology, desulfurized feed gas (with little CO and CO_2) is preheated by a gas-gas heat exchanger and then reacts in the 1# alcohol etherification system. Next, the high-temperature gases are cooled by the feed gas in the gas-gas heat exchanger. Then the feed gas (with less CO and CO_2) is preheated by the gas-gas heat exchanger, reacts in the 2# alcohol etherification system, and high-temperature gases are cooled by the feed gas in the gas-gas heat exchanger.

After this, the gases are sent to the hydrocarbon system and preheated by the gas-gas heat exchanger. They undergo reaction in the hydrocarbon tower, are cooled by the gas-gas heat exchanger, and finally the alcohol hydrocarbon hydrates are condensed and separated (Xie 2004).

EE-22: All low-temperature conversion technologies

The conversion reaction for CO is exothermic. Lower reaction temperature promotes a balance reaction. When Co-Mo is used as the conversion catalyst instead of Fe-Cr, the reaction temperature will decrease by 100~150℃. Lower temperature means lower energy consumption and CO_2 emissions (Wang and Zhang 2000, Gu 2013).

EE-23: Medium-low-low temperature conversion technology

In the conversion process, most ammonia plants use coke, steam, and air to make water gas in the UGI (United Gas Improvement) furnace. The medium-low-low temperature conversion system uses a low-temperature catalyst for the second two tandem conversion processes after the first conversion process at medium temperature. In the first stage, the medium temperatures provide for a faster reaction rate; in the later two tandem conversion stages, lower temperatures reduce energy consumption (Xu and Wang 2012).

EE-24: Combined-cycle technology

This combined-cycle technology is similar to a steam-gas combined-cycle system. The system uses a gas turbine to drive the air compressor, and the exhaust gas from the gas turbine can be sent to the first stove to promote combustion and thus reduce the energy consumption (MIIT 2012b).

EE-25: Evaporative condenser cooling technology

The evaporative condenser system uses both water and air as media to cool the high-temperature liquid refrigerant. The main cooler is evaporative (using water as the cooling medium), but air-cooled heat exchangers are also used and the combined system is optimized to reduce the electricity consumption (Zhi 2010, MIIT 2012b).

EE-26: High-efficiency rotor technology

For smaller rotors, size is the predominant factor affecting efficinecy. For larger rotors, efficiency classes are important. High-efficiency rotors reduce energy losses by their design, materials, tight tolerances, and manufacturing techniques. With proper installation, energy-efficient rotors run cooler than conventional rotors and have higher service factors, longer bearing and insulation lifetimes, and less vibration (Zhao 2009, MIIT 2012b, IETD, 2014).